AFRL-DE-PS-TR-1998-1007

AFRL-DE-PS-TR-1998-1007

Minimizing Dispersion in a Transverse Electromagnetic Waveguide Bend by a Layered Approximation of a Graded Dielectric Material

W. Scott Bigelow and Everett G. Farr

Farr Research
614 Paseo Del Mar NE
Albuquerque, NM 87123

September 1997

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

AFRL-DE-PS-TR-1998-1007

This report has been approved for publication.

WILLIAM D PRATHER, DR-III
Project Manager

FOR THE COMMANDER

EILEEN WALLING, LtCol, USAF
Chief, High Power Microwave Division

R. EARL GOOD
Director, Directed Energy Directorate

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1997	Final Report, May 97 – Sep 97

4. TITLE AND SUBTITLE

Minimizing Dispersion in a Transverse Electromagnetic Waveguide Bend by a Layered Approximation of a Graded Dielectric Material

5. FUNDING NUMBERS

C: F29601-97-C-0078
PE: 65502F
PR: 3005
TA: C0
WU: TZ

6. AUTHOR(S)

W. Scott Bigelow and Everett G. Farr

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Farr Research, Inc.
614 Paseo Del Mar NE
Albuquerque NM 87123

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFRL/DEHP
3550 Aberdeen Avenue SE
Kirtland AFB NM 87117-5776

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

AFRL-DE-PS-TR-1998-1007

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release; Distribution is Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Waveguide bends pose a problem for high-voltage ultra-wideband systems or for any transmission-line system with low-loss/fast-risetime requirements, since only a straight section of conventional transmission line can support the pure transverse electromagnetic mode necessary to preserve the risetime of a transmitted pulse. We consider alternative concepts for compensation of waveguide bends. One concept, a graded dielectric strip line bend, is built and tested. By reducing the dispersion of a transmitted voltage step, this strip line bend demonstrates the principle of compensation of a waveguide bend by a graded dielectric lens.

14. SUBJECT TERMS

TEM waveguide bend; Low-dispersion; Graded dielectric material; Dielectric lens; Ultra-Wideband

15. NUMBER OF PAGES

20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

CONTENTS

FIGURES

1. Introduction

Bends in waveguides pose a problem for high-voltage ultra-wideband (UWB) systems or for any transmission line system with low-loss/fast-risetime requirements. The difficulty arises because only a straight section of conventional transmission line can support the pure transverse electromagnetic (TEM) mode necessary to preserve the risetime of a transmitted pulse. When there is a bend in the waveguide, especially when the cross-section of the waveguide is large (as it typically must be for high-voltage or low-loss systems), the transmitted signal has a slower risetime than the incident signal. This can severely limit system bandwidth.

In several of the Sensor and Simulation Notes [1, 2, 3, 4, 5, and 6] Dr. Carl E. Baum described a new technology to address this problem. Specifically, one can embed a waveguide bend within a dielectric lens fashioned from material having a graded permittivity. Since a properly designed bend employing such a lens will support true TEM waves, even an electrically large bend can be implemented with no dispersion. Use of such bends would permit more compact and convenient designs of high-voltage UWB or low-loss systems.

Although waveguide structures employing lens materials having the required inhomogeneous permittivity profile are easily conceptualized, constructing them is more problematic. Fortunately, an approximation based on graded layers of dielectric materials of various uniform permittivities should be adequate for a pulse with a risetime comparable to or longer than the greatest difference in signal transit times through the bend for any two layers. Use of such graded layers of dielectric materials would permit economical commercial fabrication of electrically large, low-dispersion waveguide bends.

In this report, we describe the design and testing of a 90-degree bend in a TEM strip transmission line embedded in graded dielectric layers. The material presented in this report is an abbreviated version of [7], and the reader is referred to that document for additional detail.

We first provide an overview of the graded dielectric lens concept and we survey the implementation alternatives which we considered at the outset of this Phase I small business innovative research (SBIR) effort. Next, we summarize our hardware implementation of a graded dielectric strip line bend. Design information, analysis, and test results are summarized.

Although a leaky structure, such as a curved strip line, cannot be expected to perform as well, for example, as a coaxial line, it was less complex to build than a coaxial line; and it successfully demonstrated the principle of compensation of a bend in a TEM transmission line by a lens consisting of a layered approximation of a graded dielectric material.

2. Overview of the Graded Dielectric Concept

Consider the waveguide bend shown in Figure 1, which consists of a strip transmission line above a ground plane, all in air. The straight sections of the waveguide are known to support the non-dispersive propagation of a pure TEM wave, provided that the conductors are perfectly conducting—in practice, there is some dispersion due to finite conductivity. However, the curved section cannot support a pure TEM wave. This is readily understood by noting that rays entering the bend at its outer edge must travel farther than those entering at the inside edge. As a result, they lag behind those at the inside edge. What is needed is a way to equalize the transit times for all rays propagating through the bend.

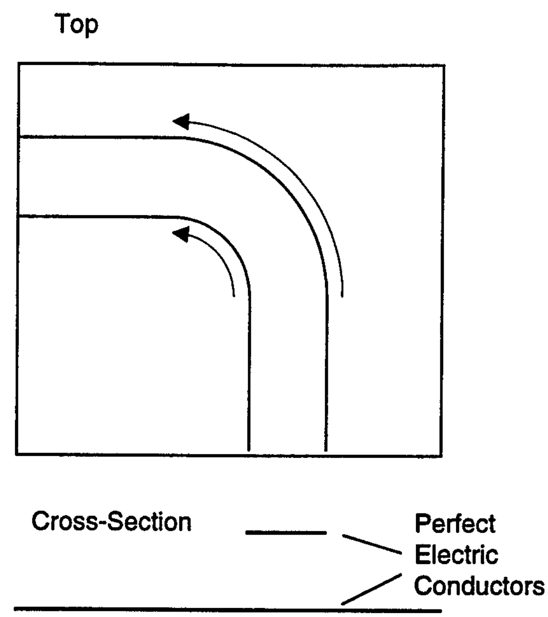

Figure 1. Waveguide bend, showing why a wave becomes dispersed at a bend. A ray on the outside curve travels farther than one on the inside.

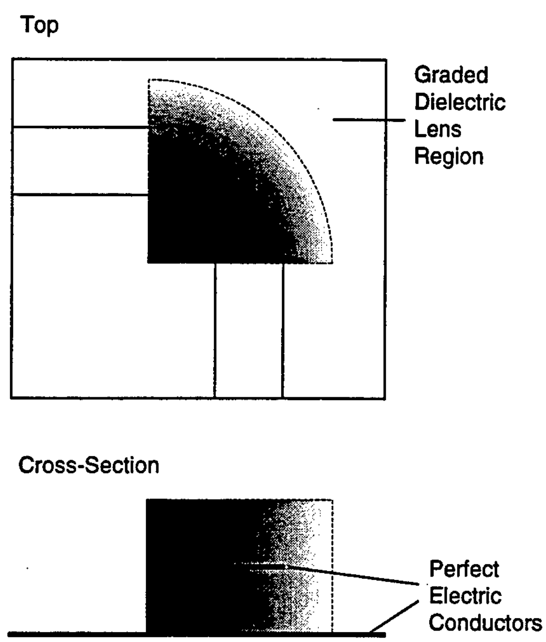

Figure 2. Compensation of a waveguide bend with a graded dielectric material. Within the bend, the permittivity varies inversely as the square of the radius of curvature.

For a purely dielectric (non-magnetic) material, a very simple method of equalizing transit times through a bend is to embed the

strip line in a material whose permittivity varies inversely as the square of the of radius. This is expressed as [2]

$$\varepsilon(\Psi) = \varepsilon_o \times \left(\frac{\Psi_{max}}{\Psi}\right)^2 \tag{1}$$

where Ψ is the cylindrical radius of curvature, and ε_o is the permittivity of free space. Here, it is assumed that at some outer radius, Ψ_{max}, the fields no longer contribute significantly; and the dielectric constant reaches a minimum, in this case ε_o. This is indicated conceptually in Figure 2.

3. Implementation of a Compensated Waveguide Bend

We considered several alternative hardware implementations of non-dispersive waveguide bends. Ultimately, we selected a strip line bend embedded within graded dielectric layers machined from sheets of low-loss uniform-permittivity plastic materials. This design represented a compromise between modeling fidelity and ease of construction. Here, we first review the other candidate approaches we considered. Then we discuss the design and testing of the graded dielectric strip line bend.

3.1 Approaches Considered

The first approach considered was to build cylindrical layers having differing permittivities by using combinations of epoxy and titanium dioxide powder. In this approach, one would add successive layers to the inside of a cylinder, with each layer having a slightly higher permittivity than its predecessor. One would make each layer uniform by spinning the cylinder at a high angular speed, as indicated by Figure 3. A similar approach might be useful for building up layers inside a coaxial bend. One can anticipate, however, a number of difficulties in working with the mixtures of epoxy and titanium dioxide. A well-controlled process would have to be used to control the blending of the mixtures, and a

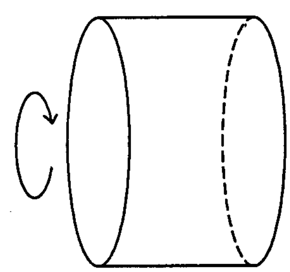

Figure 3. Graded dielectric fabrication technique using successive layers of epoxy loaded with titanium dioxide.

similarly well-controlled process would be needed to deposit and cure each layer. While these obstacles could likely be overcome in a production-scale facility, they would have posed unnecessary difficulties for an initial proof-of-principle hardware demonstration.

Another option considered was to build the dielectric material from a uniform material, such as circuit board laminate, by use of cylindrical sheets of the material arranged to form a saw-tooth pattern. This would simulate a graded dielectric material. A diagram of this idea is shown in Figure 5. A further simplification of this approach would be the use of a single cylindrical wedge, as shown in Figure 4. The single wedge could be readily cut under computer control and its use would obviate the complex assembly process required for a stack of sheets.

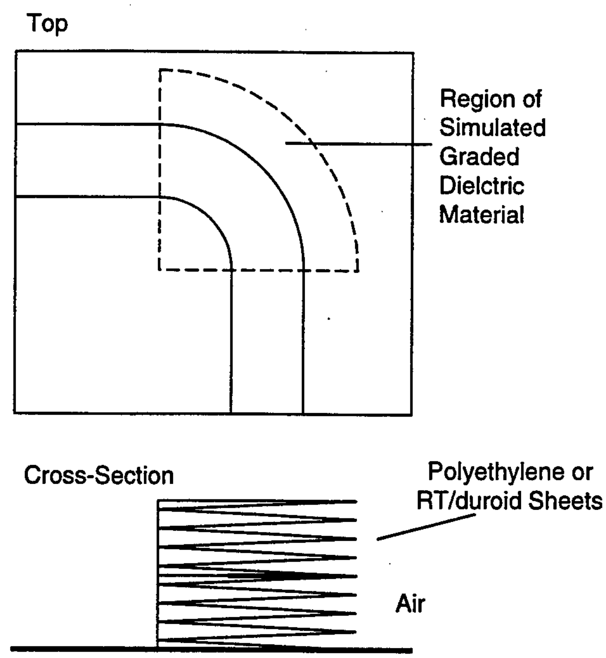

Figure 5. One method of building a simulated graded dielectric material, using a stack of uniform-permittivity wedges in a saw-tooth pattern.

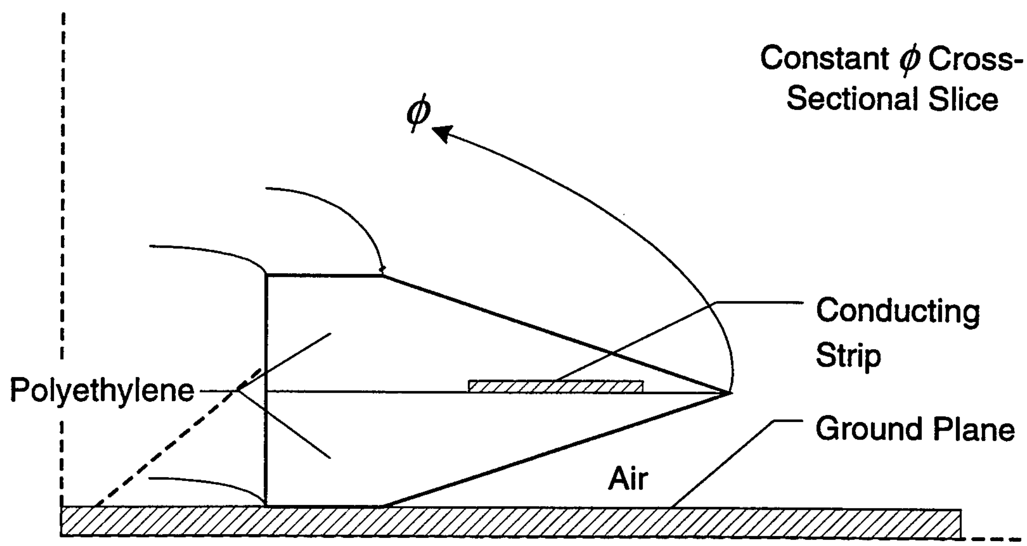

Figure 4. Strip line bend partially filled with dielectric in the form of a single cylindrical wedge.

A disadvantage of these uniform material configurations is that the resulting effective permittivity is anisotropic. In other words, at a given point there is a different permittivity for electric fields polarized horizontally and vertically. This is potentially a problem, because the theory assumes an isotropic material.

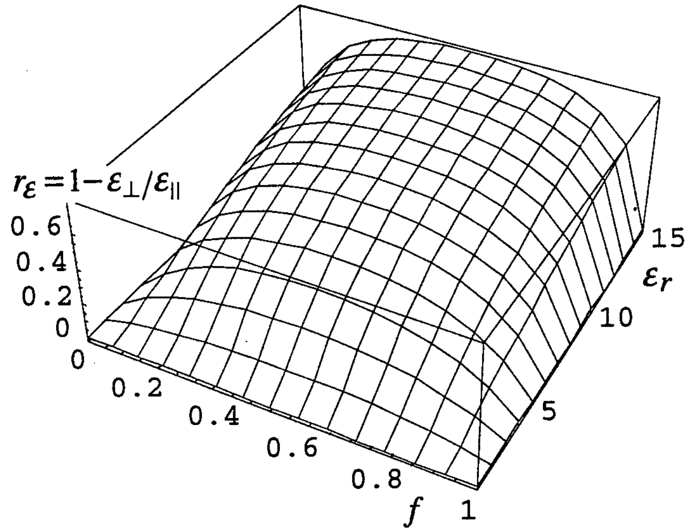

Figure 6. Anisotropy of the effective relative permittivity for a parallel plate capacitor partially filled with a uniform dielectric material.

Figure 6 demonstrates that the anisotropy in the effective permittivities, quantified by $r_\varepsilon = 1 - \varepsilon_\perp/\varepsilon_\parallel$, increases with the permittivity of the fill material and is largest for a half-filled capacitor.

Another bend compensation approach considered was that of embedding wedges of high-permittivity materials in a direction perpendicular to the direction of propagation. A sketch of this concept is shown in Figure 7. Because of the differing radii of curvature, there is relatively more high-permittivity material along the inner curve than along the outer curve. By adjusting the number and thickness of the wedges, the profile of the effective permittivity may be tailored. Here, there is no difficulty with anisotropy, since the fields are parallel to the dielectric-air interfaces. However, the granularity of the wedges must be sufficiently fine that the wedge transit times remain short compared to the risetime. Also, multiple reflections from the wedge surfaces could be a problem. As a result, this approach could be more useful with an E-plane bend, where it might be possible to minimize reflections by arranging the dielectric surfaces at Brewster's angle relative to the electric field vector.

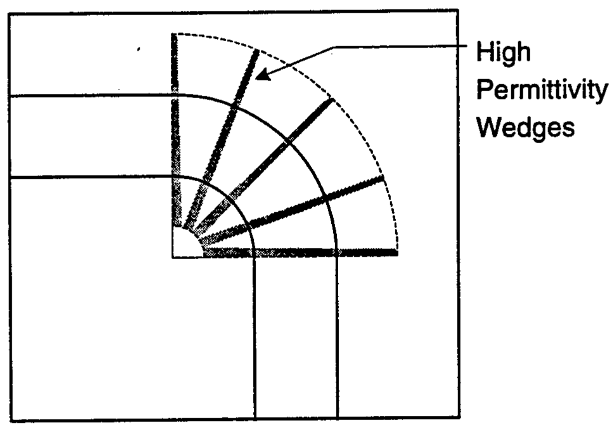

Figure 7. Use of high-permittivity wedges oriented radially.

3.2 Design and Testing of the Graded Dielectric Strip Line Bend

We now describe the design and testing of a layered approximation of a graded dielectric material as a compensating lens for a strip line bend. Our test fixture layout is depicted in Figure 8. Details of the wave launcher region are shown in Figure 9; details of the dielectric material layout in the bend region are shown in Figure 10. With the straight section in place, measurements were made between Port 1 and Port 2. With the curved section, measurements were made between Port 1 and Port 3. The curved section was used both with and without the graded dielectric lens.

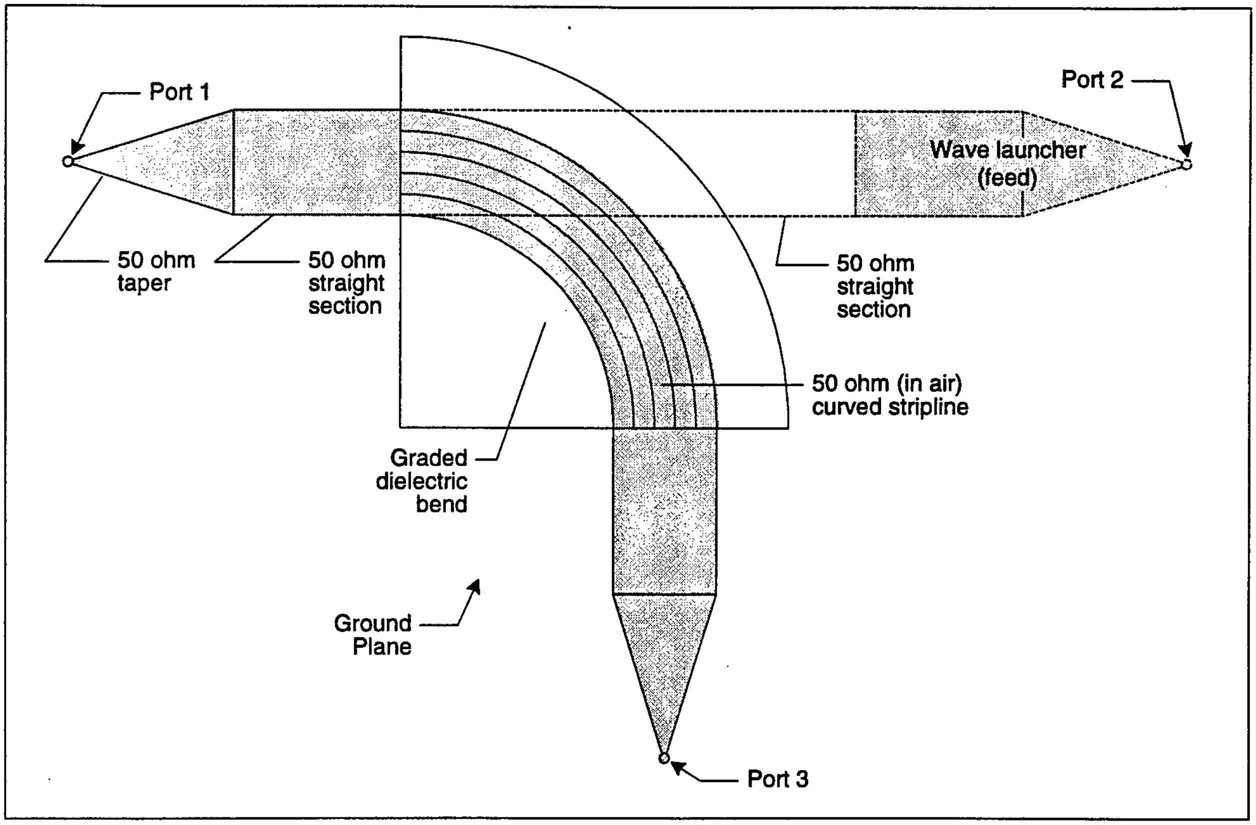

Figure 8. Strip line test fixture geometry.

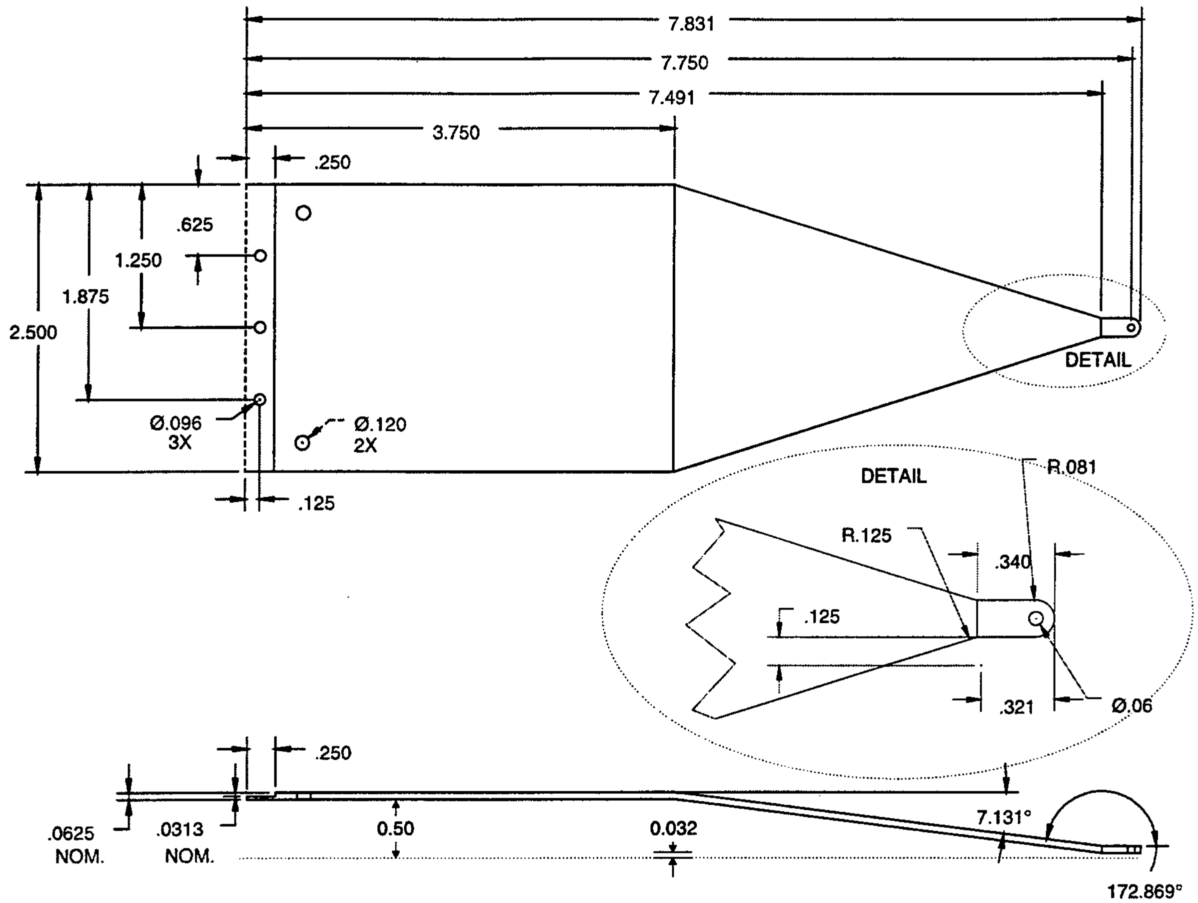

Figure 9. Detail of the test fixture wave launcher design. A constant 5:1 width-to-height ratio is maintained throughout.

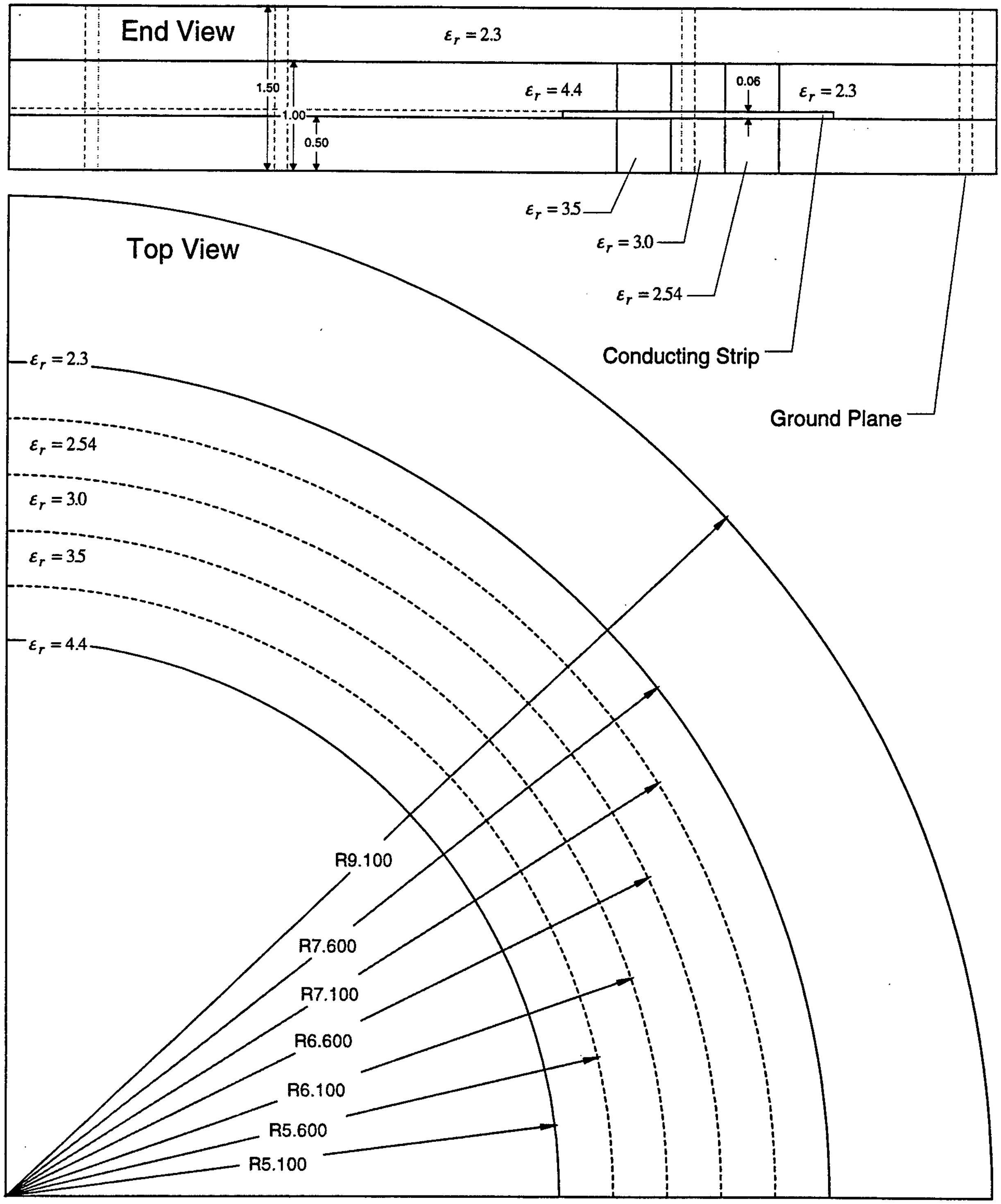

Figure 10. Five-region graded dielectric bend assembly. Straight sections at the entrance and exit of the bend are not shown. The conducting strip is 0.5 inches above the ground plane. Its width is a constant 2.5 inches in both straight and curved regions. Within the strip boundaries, the relative permittivities approximate an inverse square law relationship with the radius of curvature. The relative permittivity is assumed to be 1.0 at a radius of 11.0 inches.

To find the characteristic impedance of the graded dielectric structure, one solves a two-dimensional equation in cylindrical coordinates, in a plane of constant azimuth, ϕ. In terms of the electric potential, $V(\Psi, z)$, the equation to be solved is [6 (7.9)]

$$\Psi \frac{\partial}{\partial \Psi}\left(\frac{1}{\Psi}\frac{\partial V}{\partial \Psi}\right) + \frac{\partial^2 V}{\partial z^2} = 0 \tag{2}$$

where the boundary conditions are $V = V_0$ on the conducting strip and $V = 0$ on the ground plane. To maintain a constant wavefront velocity around the bend, the dielectric constant, ε, must vary inversely as the square of the radius in the bend region, as specified previously in (1). In principle, one can then calculate the charge per unit angle (ϕ) on the center conductor. From the charge per unit angle and the angular wave propagation speed around the bend (in radians per second), the current may be obtained. With the current and voltage calculated, the characteristic impedance is their ratio.

As an approximation, we chose to solve a simpler problem using the finite element method. We assumed that the change in azimuth through the bend could be ignored—a straight strip approximation. This permitted us to treat Ψ and z as Cartesian coordinates, and reduced our problem to solving Laplace's equation,

$$\nabla \bullet (\varepsilon_i \nabla V) = 0 \tag{3}$$

over a rectangular (Ψ, z) domain consisting of piecewise-constant-permittivity ($\varepsilon_i = \varepsilon_{r,i}\, \varepsilon_0$) subdomains. This method produced a characteristic impedance of 28 ohms, in agreement with a TDR measurement of the bend (Figure 11).

As a further check on the validity of our numerical approximation, we also modeled the bend using three different analytic approximations. A closed-form analytic result for a pair of infinitesimally thin plates immersed in a uniform dielectric—a straight strip approximation, which includes the fringe field contribution—yields a characteristic impedance of 98 ohms in air (see, for example, [8, 9, 10, and 11]). This is equivalent to 28 ohms for a single plate over a ground plane and an effective relative permittivity of 3.1 (the average for the materials used in the bend). For the same one-half parallel plate transmission line, in which both plate thickness and fringe fields are neglected, the calculated characteristic impedance is 43 ohms. An approach described by Baum [2] produces a closed-form solution to (2) for a continuously graded H-plane

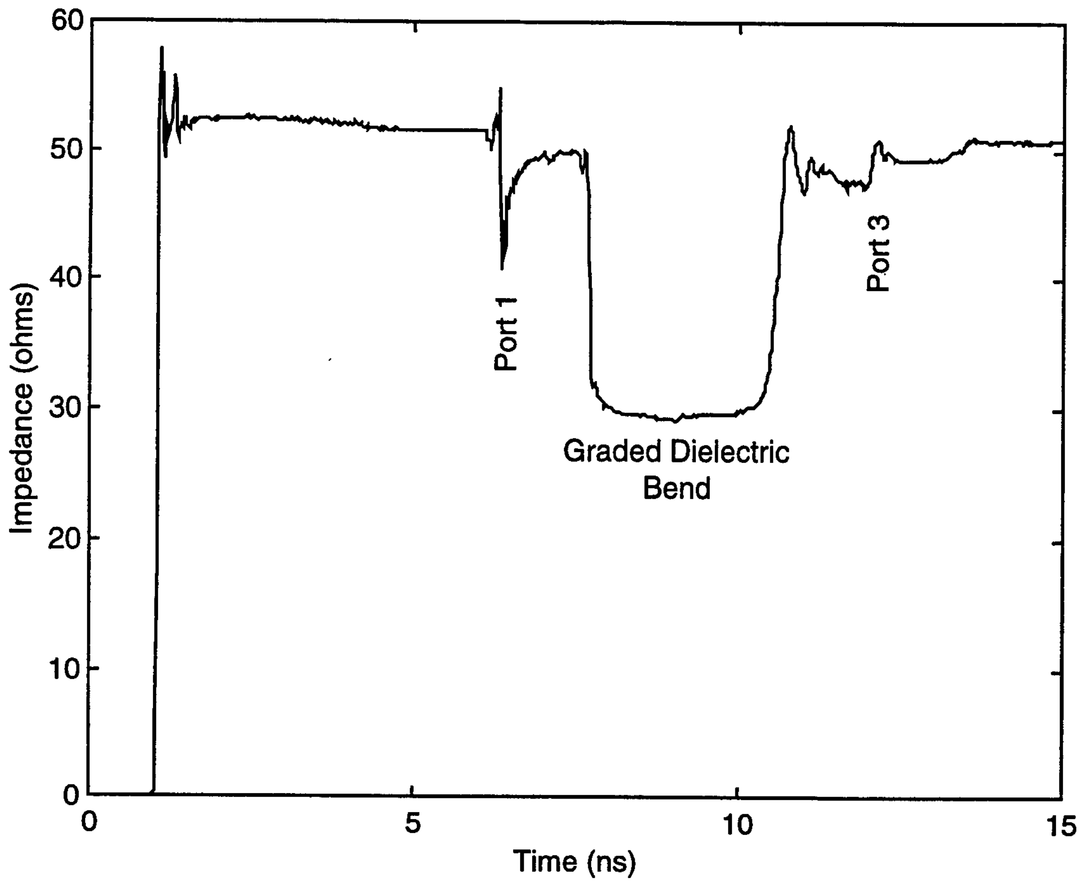

Figure 11. TDR of a strip line with a 90-degree bend filled with graded dielectric materials. Within the bend region, the impedance is approximately 28 ohms.

bend, subject to the assumption that fringe fields can be neglected. That approach also leads to a value of 43 ohms.

Since both graded bend and parallel plate impedance results (neglecting fringe fields) are in agreement, we have confidence that our straight strip approximation to the bend is a good approximation. In turn, this conclusion gives us confidence that the 28 ohm straight strip results, produced by both the analytic and the finite element numerical methods, represent good approximations for the graded bend, when fringe fields are considered. Thus, both measurement and numerical analysis agree that 28 ohms is a good estimate of the characteristic impedance of the graded bend.

In Figure 12, transmission of a voltage step pulse through the straight, air-filled strip line section (between Port 1 and Port 2), is compared with transmission of the same pulse through the curved section (between Port 1 and Port 3), both air-filled and compensated by the five-layer graded dielectric lens. The data for the compensated bend were normalized to remove the 8% reflection loss that results from traversing the two dielectric–air interfaces. Transmission through the straight strip line section (and the feed sections) degraded the fall time to 75 ps. This is the best we can expect for a perfectly compensated curved section. The air-filled bend degraded the fall time to 255 ps. The graded dielectric filler improved the transmission through the bend, reducing the fall time to 185 ps. However, this is still more than twice the fall time observed with the straight strip line section.

The primary causes of the imperfect compensation of the bend appear to lie in the finite thickness of the dielectric layers, and in the permittivities of the materials filling the fringe field

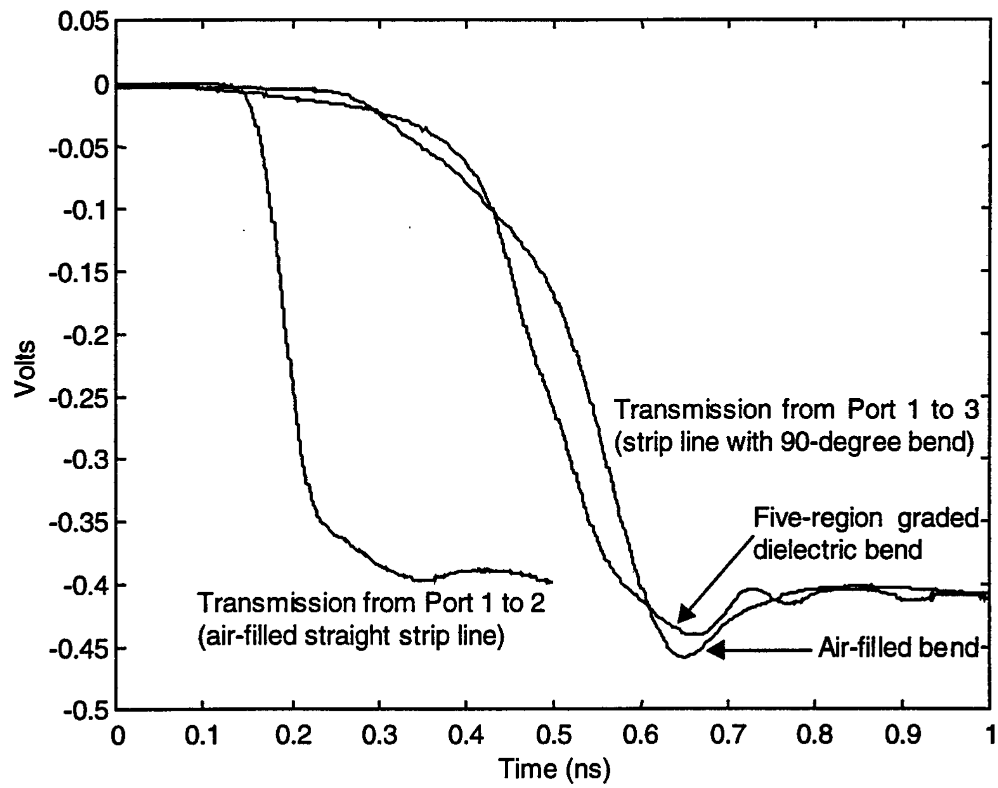

Figure 12. Transmission of a voltage step by straight and bent strip lines. The fall time for the straight line is about 75 ps. With the air-filled, 90-degree bend, the fall time increases to about 255 ps. For the same bend with a five-layer radially graded dielectric lens, the fall time is reduced to about 185 ps. The data are normalized to correct for reflection losses at the dielectric-air interfaces.

regions on each edge of the strip. The difference in transit time around the bend at the strip edges is 330 ps for the air bend; for the lensed bend, the difference is only 110 ps. However, the transit time difference for the lensed bend climbs to 350 ps when fringe regions 1.27 cm on each side of the strip are considered. If we calculate the transit times along each dielectric layer interface, we find that the differences in transit times within the dielectric layers immediately adjacent to each interface range from a low of 74 ps to a high of 170 ps. All these differences in transit time combine to stretch the transmitted pulse.

Other contributors to the observed imperfect compensation of the bend are pulse distortion resulting from the impedance discontinuities at the entrance and exit of the bend, and dispersive attenuation of the transmitted pulse.

4. Conclusions

Although the five-layer graded dielectric bend substantially improved the transmission of a stepped voltage pulse through the curved section of our strip line test fixture, the fall time of the pulse was still more than twice that observed for propagation through an equivalent straight section. Several features of the design may contribute to this situation. Among the significant design issues are: (1) the accuracy of the graded layer approximation to the ideal continuously graded bend, (2) pulse distortion at the impedance discontinuities at the entrance and exit of the bend, and (3) dispersive attenuation of the pulse.

Inaccuracies in the layered approximation of the graded dielectric bend led to significant differences in pulse transit time through the bend. The transit time differences introduced by the fringe field regions were especially large. Thus, variations in transit time through the bend appear to have been major contributors to the observed pulse stretching.

Although the impedance discontinuities at the entrance and exit of the bend led to reflection losses on the order of 8%, no other negative impacts on the transmitted pulse are apparent. Since the reflective losses appear to account for the degradation in the magnitude of the transmitted pulse, attenuation by the dielectric material does not appear to be a significant issue.

In the future, we plan to design a graded coaxial transmission line bend. This should be almost as easy to fabricate as the leaky strip line, and fortunately, fringe fields will not be an issue for a coaxial geometry. We anticipate that a finely-graded coaxial line will be capable of extremely low-dispersion transmission. Moreover, by eliminating dielectric-air interfaces, we will be able to reduce reflective losses.

References

1. Baum, Carl E., *Two-Dimensional Inhomogeneous Dielectric Lenses for E-Plane Bends of TEM Waves Guided Between Perfectly Conducting Sheets*, Sensor and Simulation Notes, Note 388, 14 October 1995.

2. Baum, Carl E., *Dielectric Body-of-Revolution Lenses with Azimuthal Propagation*, Sensor and Simulation Notes, Note 393, 9 March 1996.

3. Baum, Carl E., *Dielectric Jackets as Lenses and Application to Generalized Coaxes and Bends in Coaxial Cables*, Sensor and Simulation Notes, Note 394, 23 March 1996.

4. Baum, Carl E., *Azimuthal TEM Waveguides in Dielectric Media*, Sensor and Simulation Notes, Note 397, 31 March 1996.

5. Baum, Carl E., *Discrete and Continuous E-Plane Bends in Parallel-Plate Waveguide*, Sensor and Simulation Notes, Note 399, 1 May 1996.

6. Baum, Carl E., *Use of Generalized Inhomogeneous TEM Plane Waves in Differential Geometric Lens Synthesis*, Sensor and Simulation Notes, Note 405, 5 December 1996.

7. Bigelow, W. Scott, and Everett G. Farr, *Minimizing Dispersion in a TEM Waveguide Bend by a Layered Approximation of a Graded Dielectric Material*, Sensor and Simulation Notes, Note 416, 5 January 1998.

8. Farr, Everett G., *Optimization of the Feed Impedance of Impulse Radiating Antennas Part II: TEM Horns and Lens IRAs*, Sensor and Simulation Notes, Note 384, November 1995.

9. Farr, Everett G., *Optimizing the Feed Impedance of Impulse Radiating Antennas, Part I, Reflector IRAs*, Sensor and Simulation Notes, Note 354, January 1993.

10. Baum, Carl E., D. V. Giri, and R. D. Gonzalez, *Electromagnetic Field Distribution of the TEM Mode in a Symmetrical Two-Parallel-Plate Transmission Line*, Sensor and Simulation Notes, Note 219, April 1976.

11. Baum, Carl E., *Impedances and Field Distributions for Parallel Plate Transmission Line Simulators*, Sensor and Simulation Notes, Note XXI, June 1966.

DISTRIBUTION LIST

AUL/LSE Bldg 1405 - 600 Chennault Circle Maxwell AFB, AL 36112-6424	1 cy
DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	2 cys
AFSAA/SAI 1580 Air Force Pentagon Washington, DC 20330-1580	1 cy
AFRL/PSOTL Kirtland AFB, NM 87117-5776	2 cys
AFRL/PSOTH Kirtland AFB, NM 87117-5776	1 cy
Farr Research 614 Paseo Del Mar NE, Albuquerque, NM 87123	3 cy
AFRL/DEHP/Mr Jon Hull	1 cy
Official Record Copy AFRL/DEHP/William Prather	1 cy